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MICROWAVE PROPAGATION IN MARITIME ENVIRONMENT

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ABSTRACT

A simple question that arises when dealing with maritime communications is: How would one offload large quantities of data from sea to shore and vice versa if one cannot use conventional solutions such as satellite communications or cellular data? In this note we describe the first prototype solutions that were produced. They gave rise to SeaFi, which has become an enabling technology in the context of oceanic and coastal research. Measurements at sea are key to scientific research project such as for exemple HIGHWAVE, a recently started ERC Advanced Grant project that relies partly on the possibility to measure breaking waves in realtime. Since the bottleneck is the real-time transmission of data, transferring measurement data at sea using SeaFi instead of using conventional satellite communications or cellular data connection, quickly became an evidence. To assess the possibilities, a series of offshore experiments were performed from May to July 2018. Those experiments led on June 6th, 2018 to a world record for the longest wireless microwave transmission at sea, between a moving ship and a lighthouse, using the SeaFi communication system. In addition, the proposed solution also promises a better future for lighthouses around the world that are now gradually falling into disuse. This breakthrough in maritime telecommunications could change the way scientific researchers retrieve data in real time at sea in the coming years.

KEYWORDS: Real-time data, WiFi at sea, microwaves, antennas, data transmission

1. INTRODUCTION

Whereas some data buoys or oil and gas rigs can be connected by optical fiber laid out on the seafloor, there are realistically only two options at present when dealing with large datasets on a

ship/deep water data buoy at sea: satellite or cellular. But neither was designed to deal with large scale marine datasets. Integration of satellite communications on a buoy or an Unmanned Surface Vehicle (USV) is costly. Cellular data is only sporadically available at sea. SeaFi, with wireless microwave transmission, offers a new third option specifically designed for large-scale marine data environments. The large-scale offshore experiment described in this paper, which took place on May 5th and June 6th, 2018, is a proof of concept.

In telecommunications, wide bandwidth data transmissions conveying multiple signals are also referred to as broadband. Data transmission refers to a digital bitstream over a point-to-point or even point-to-multipoint communications channel. The carrier can be a coaxial cable, optical fibre, radio or a twisted pair of copper cables. In wireless communication channels, the data are represented as an electromagnetic signal, such as an electrical voltage, radio wave, microwave, or infrared signal.

The first SeaFi prototype, developed in 2012, simply aimed to connect a local service vessel (tug) to the internet using conventional *off the shelf* WiFi equipment. It quickly proved not to be suited to the maritime environment. It was too fragile and had a poor tilting tolerance at sea. The prototype evolved into a rugged seaworthy piece of equipment designed for ships and data buoys. With support from the Irish Naval Service, sea trials involving Offshore Patrol Vessels (OPVs) and Rigid Inflatable Boats (RIBs) showed greater potential. This is when we decided to build our own equipment. The system would be drawing from Wireless Internet Service Providers (WISP) standards but, additionally, require more robust antennas on shore. By 2014, the concept of a **Wireless Maritime Area Network (WMAN)** was born and, with it, a new way of building smarter

cost-effective ports and intelligent coastlines, as well as offshore renewable and salvage operations, without compromising throughput, security or data transfers.

Beyond scientific data collection, the applications for SeaFi can also be of societal nature. In 2017 an experiment was conducted aboard the MV Stena Horizon to demonstrate the superiority of WMAN in a port. It has since caught the attention of the maritime community in the UK and Ireland. Besides improving security and business efficiency and providing much lower communication costs, SeaFi offers the possibility of greatly improving links of sea workers with their families during long absences.

The goal of the large-scale offshore experiment was to assess the resilience of a wireless microwave link while determining the furthest practical maritime broadband transmission without a satellite or cellular network, using the SeaFi wireless maritime communication system between a moving ship and a lighthouse. The SeaFi experiment of June 2018 demonstrated the superiority in terms of reliability and running costs of the SeaFi wireless microwave link over conventional technologies such as satellite or cellular data communications. This experiment brought permanent access to the ship equipment from the shore side (remote connection). Using an Offshore Supply Vessel (OSV) operating on the same route, instead of an OPV, allowed controlled observations depending on:

1. Coastal and seaboard antenna design
2. Horizontal and vertical alignment
3. Accurate space diversity to counter reflections
4. Variation in atmospheric conditions
5. Multi-path propagation delay

6. Ship course and local diffraction
7. Reflected signal (ship structure and sea water)
8. Refraction in sea water and signal loss.

In this note, we first describe the various communication methodologies. We then provide an account of the experiment. Finally, we discuss the outcomes of the experiment.

2. COMMUNICATION METHODOLOGIES

2.1 Cellular networks and satellite communications

Invented to satisfy the growing demand for data from mobile phones, the 3G/4G cellular network is expensive to put in place, and so is primarily used in larger population areas. The availability of 3G/4G at sea is purely coincidental and unreliable, as it was never designed for this type of use. So, when networks become overloaded (saturated networks phenomenon), the units most remote from the mast are generally the first to be disconnected from the network. Cellular was originally invented for mobility with station roaming from cell to cell, for example a phone in a car travelling on the motorway.

Cellular networks data capacity is often increased by splitting cells to reduce the size, and thus increase the number of cells serving a given area. This is done by deploying more radio towers/antennas and shrinking the reach of each tower by reducing the radiated power of its radio transmissions. This allows the radio spectrum to be reused for multiple simultaneous transmissions within the geographic area. It also increases the amount of traffic that a Hz of spectrum can carry within an overall geographic area (measured by bps/km²). But while effective at deepening wireless network capacity, this method is also expensive – requiring the construction of extra

towers/antennas, deploying more radios and base station equipment, as well as extending additional backhaul links to link new towers back into the mobile operator's core network (Clarke, 2014).

Specifically designed for maritime use, the Iridium satellite system is theoretically based on 80 satellites. The first generation of satellites that was put in orbit between 1997 and 2002 (at a cost of \$5 billion) is now reaching *end of life* in orbit with the new generation satellites taking over (Iridium Satellite Constellation, 2019). Technically, a satellite is a WiFi system where the base station access point (the satellite) is 700 km away from the vessels (the station) allowing communication under the horizon. The satellite concept designed when smartphones did not exist must now face the bottlenecked era of the all-connected Internet of Things (IoT). More recent projects such as Amazon, Starlink and OneWeb are promoting Low Orbit Satellites, which together with Nanosatellites (satellite weighing less than 10 kg), seem to be the most popular commercial solution in the next decade (Boiardt & Rodriguez, 2010).

2.2 SeaFi in a nutshell

SeaFi facilitates the creation of private networks in ports and coastal areas by enabling microwave connections without relying on conventional telecommunications infrastructures (Figure 1). These networks can be used to connect, for example, lighthouses, maritime wind turbines, offshore drilling platforms, sea tugs, gantry cranes, data collection buoys and wave energy converters. But SeaFi can also work in ship-to-ship mode, and be combined with satellite communications to connect, for example, ships during salvage operations or ships with oil and gas platforms.

SeaFi is an S band radio system, where S stands for "short" wave, not to be confused with the short-wave radio band, which is much lower in frequency. SeaFi is operating on the 2.4 Gigahertz (GHz) frequency, using interconnected coastal stations (connection access points) and embarked stations at sea. This frequency is gradually being abandoned on shore because of its channels limitation and hardly used at sea. Fourteen channels are designated in the 2.4 GHz range, spaced 5 MHz apart from each other.

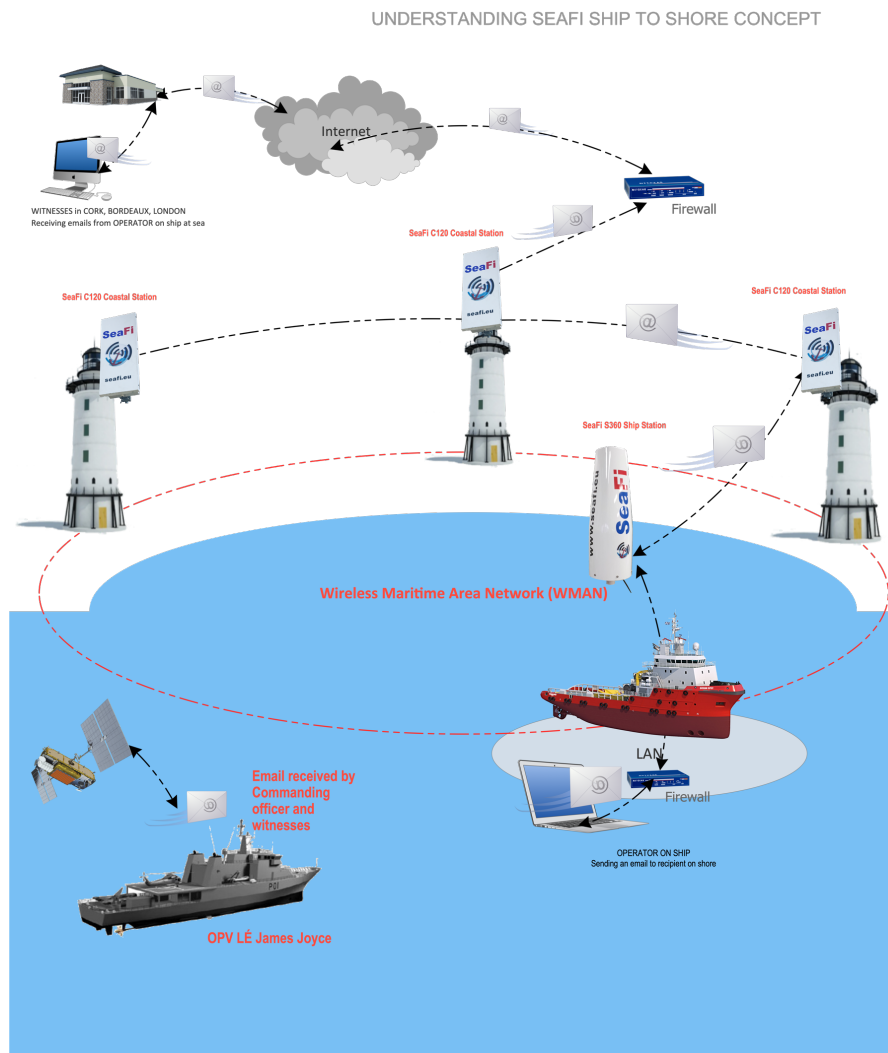


Figure 1 : Wireless Maritime Area Network (WMAN) representing Irish Navy vessel Offshore Patrol Vessel (OPV) acknowledging transmission from Offshore Supply Vessel (OSV) using SeaFi.

SeaFi is based on industry standards like the 802.11 wireless standard that was developed by the Institute of Electrical and Electronic Engineers, while its antennas are designed to withstand the

harshest conditions of maritime environment, including humidity, salinity, rain fade, rolling, pitching and wind.

3. THE EXPERIMENT

3.1 The purpose of the experiment

The main purpose of the experiment was to assess the longest possible distance at which the signal from SeaFi's bespoke maritime WiFi service is still reliable. Lining up irrefutable evidence of an invisible point at sea where intangible events occurred on a ship is not easy. A large-scale field-testing environment involving a series of coastal stations was setup on the south coast of Ireland. The experiments reported in this document focus essentially on the coastal station located on Roches Point lighthouse 25 m above sea level and one ship station located south of the lighthouse on board the OSV Ocean Spey.

3.2 The coastal station technical layout

The lighthouse of Roches Point was first connected to the internet in 2013. The internet connection is provided by SeaFi Port of Cork WMAN (Figure 1). The WMAN network is composed of a series of 10 interconnected coastal stations. The main junction point with the internet is in a secured bastion on Mitchell's Fort on Spike Island exactly 2.75 nautical miles (NM) away. The C180 radio transmission equipment is located on the south side of Roches Point lighthouse below the lantern to avoid any obstruction to the light quadrants 90°-210° (120°).

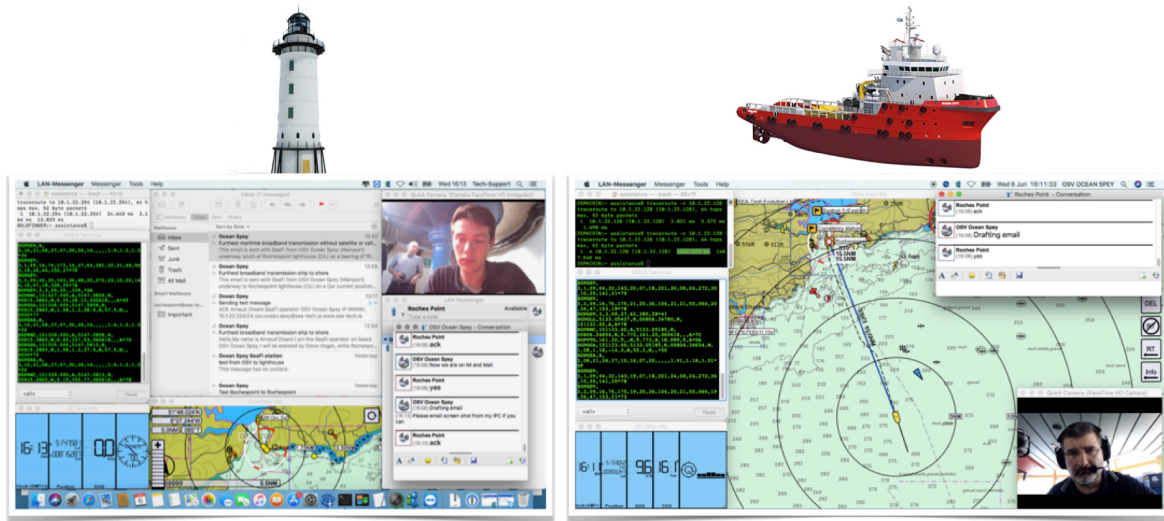
3.3 The ship station technical layout

The ship station was at the base of the mast in a Faraday cage-type compartment such that the only way in or out for the radio signal was the SeaFi S360 antenna, positioned approximately 25 m above sea level (Figure 2).



Figure 2 : The photo shows the OSV Ocean Spey passing in front of Roches Point lighthouse on May 9th, 2018, during the shakedown cruise. All the evidence used in this note is dated and all photos are also geolocated.

The SeaFi ship station was composed of a firewall, a radio and an omnidirectional antenna. The smart cabinet enclosing all the transmission was not radio transparent and located in a metal fireproof bunker (battery compartment with no windows). This cabinet was closed and did not let radio waves through. As such, the equipment couldn't receive the signal of a GPS nor any cellular data for that matter.



Rochespoint SeaFi operator

OSV Ocean Spey SeaFi operator

Figure 3 : SeaFi operator consoles showing GPS positions and OSV moving at a speed of 9.6 kts with SeaFi enabled IP cameras, emails, instant messaging connection. OSV Ocean Spey SeaFi operator also performed a Skype call with several newspaper magazines in Ireland and UK.

3.4 Before the experiment

To define the furthest point at sea where the internet connection is still useable, while a ship is moving at a speed of 10 knots and radio waves are travelling at the speed of light, meaningful tests had to be designed. The OSV Ocean Spey was connected to SeaFi Port of Cork WMAN at 14:45 on May 9th, 2018 for the *shakedown cruise*. The fine tuning of the antenna was done at sea. The software had been pre-configured in the workshop. Witnesses were carefully appointed, to encompass a wide array of skills from mathematics to technology. A few hours before the experiment on June 6th, the witnesses inspected the SeaFi ship station on board the OSV Ocean Spey in the Ringaskiddy Deep Water Berth. The bridge and the mast of the ship were searched for any trace of internet connectivity other than the SeaFi radio link.

3.5 During the experiment

The observations of the witnesses were recorded independently from each other, which allowed cross-verification of observations. At exactly 14:00 on June 6th, 2018, the OSV Ocean Spey left port, setting course south of Roches Point lighthouse in Cork Harbor. For several hours, every 15 minutes, the operator on the bridge of the Ocean Spey sent emails to the witnesses and made Skype calls to recipients in Cork and London. The witnesses confirmed in real time that the emails originated from the SeaFi ship station. Each email sent to shore from the ship was delivered without satellite nor cellular connection. Some witnesses with ICT expertise performed tests such as trace route, IP lookup, after reading email headers information to verify the unique public IP address of the Port of Cork WMAN. Since the email test could be sent remotely, the team on board the Ocean Spey also decided to do undisputable real time Skype calls with witnesses in Ireland and UK. The calls were recorded and can be viewed in a video available on YouTube.

★ Ocean Spey SeaFi station SEA-Trials (GWBR) 9 May 2018 at 21:33

Re: Test message from SeaFi Station on board OSV OCEAN SPEY

To: Damien O'Sullivan, Frederic Dias, Martin Brett, Technical Support, David Smith

Looking into the header of each email it's possible to find an IP address, it will read:

Received: from [10.1.22.242] ([91.142.103.182]) by smtp.gmail.com

- 91.142.103.182 is the public IP address of the Internet Service Provider supplying Internet access to SeaFi Port of Cork WMAN
- 10.1.22.242 is the WMAN IP address of the machine located inside the smart cabinet aboard OSV Ocean Spey. It proves this email was not sent from the shore using Google webmail interface.

Received: from mail-esl-f41.google.com (mail-esl-f41.google.com. [209.85.220.41]) by mx.google.com with SMTPS id w23-v6sor19069709edr.0.2018.05.09.13.33.23 for <tech-support@sea-tech.ie> (Google Transport Security); Wed, 09 May 2018 13:33:23 -0700 (PDT)

Received: from [10.1.22.242] ([91.142.103.182]) by smtp.gmail.com with ESMTPSA id q30-v8sm15746313edc.93.2018.05.09.13.33.22 (version=TLS1_2 cipher=ECDHE-RSA-AES128-GCM-SHA256 bits=128/128); Wed, 09 May 2018 13:33:22 -0700 (PDT)

Lookup IP Address Location For IP: 91.142.103.182	
Continent:	Europe (EU)
Country:	Ireland 🇮🇪 (IE)
Capital:	Dublin
State:	Cork
City Location:	Cork
Postal:	T23
ISP:	Nova Networks Ltd
Organization:	Nova Networks Ltd

Nova Networks based in Carrigtohill, Co. Cork is a Wireless Internet Service Provider (WISP) not a satellite communication provider...

Figure 4 : Emails sent are tagged with the public IP address of the sender, in the case of Port of Cork WMAN, the public IP address assigned by the Internet Service Provider is easily traceable.

At exactly 16:31, Roches Point issued one last message to the ship station. At 16:32, the SeaFi ship station on the Ocean Spey went silent after 2.5 hours of uninterrupted transmission. The OSV Ocean Spey was identified at this time by the Irish Naval Service vessel LÉ James Joyce, which

was patrolling south west of the position of the Ocean Spey. The Commanding Officer of LÉ James Joyce confirmed the reporting of the position of the Ocean Spey at Lat 51 30.05N Lon 08 03.70W – 19.4 NM (or 35.9 km) from Roches Point at the time the last transmission was made.

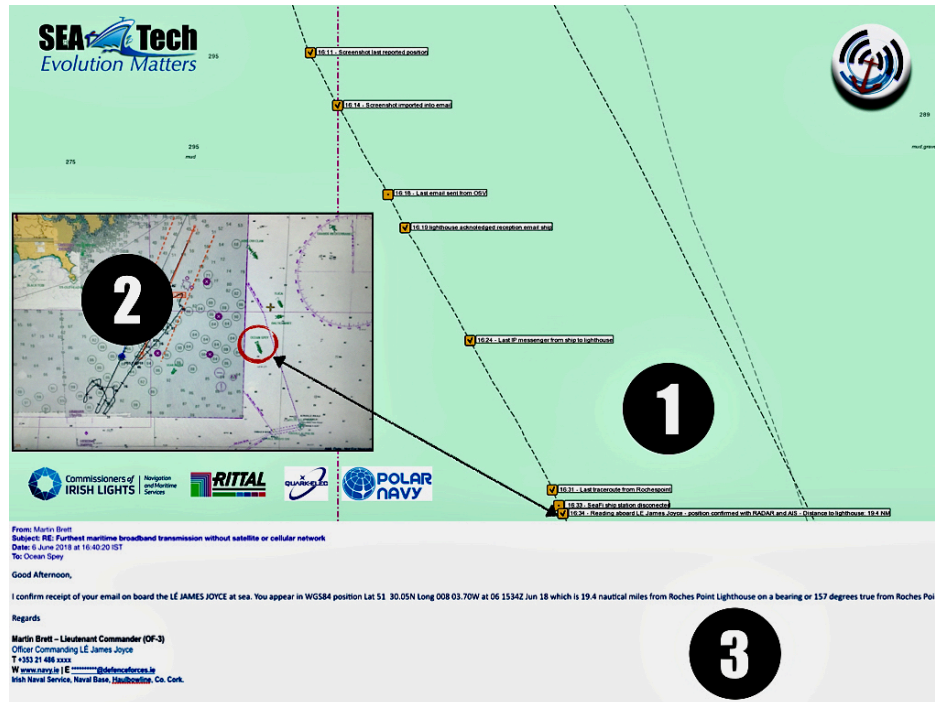


Figure 5 : OSV Ocean Spey position at 16:33 on June 6th, 2018 when connection was lost and exact position was read on radar by the commanding officer of the OPV LÉ James Joyce having received the 16:18hrs email from SeaFi operator on board the OSV.

4. RESULTS

Although the main objective of the experiment was to assess the longest distance at which the microwave signal was still useable for data transmission, the signal attenuation was also studied. All channels could be used for communications reliably to 22 NM or more with low transmitter power. It is evident from the following data, however, that there were some shortcomings due to setting up the antenna on the upper deck (Figure 6).

All electromagnetic radiation propagates at a velocity of 3×10^8 m/s in vacuum. Although wavelengths of radio waves are on the order of 10^3 m while those of light waves are on the order

of 10^{-5} cm and gamma rays on the order of 10^{-10} cm or shorter, all propagate at the same velocity through a common medium.

For two high-orbit satellites, for example, microwave transmission consists in pointing the antennas towards each other and launching the wave into space. Since the wave obeys the well-known Friis equation (Friis, 1946; Kopp, 2000), its intensity is inversely proportional to the square of the distance. On earth, more parameters come into play to affect the signal. Low-frequency radio waves travel easily through brick and stone and very low frequency (VLF) waves even penetrate seawater. As the frequency rises, absorption effects become more important. At microwave or higher frequencies, absorption by molecular resonances in the atmosphere (mostly from water and oxygen) is a major factor in radio propagation at sea (Liebe, 1985). For example, in the 58–60 GHz band, there is a major absorption peak which makes this band useless for long-distance use (Federal Communications Commission, 1997). While all visible light, most radio light, and some infrared light passes through the atmosphere, the atmosphere blocks most ultraviolet light (UV) and all X-rays and gamma rays from reaching the surface of Earth. Heavy rain and falling snow also affect microwave absorption. On earth, radio waves are subject to distortion, diffraction, refraction and reflection. At sea level this is made even more complex by natural phenomena such as water absorption and sea surface reflection.

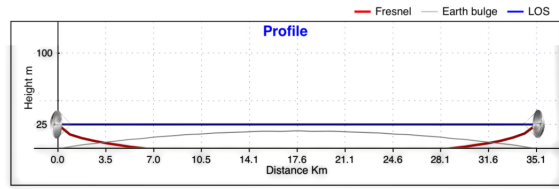
Algor (1972) measured propagation loss at three frequencies (30, 140, and 412 MHz) over various sea-water paths out to 40 NM between a moderately elevated shore-based receiving site and a floating transmitter platform subject to wave motion. Experiments were conducted in order to determine the frequency region most conducive to trans horizon communications over a sea-water

path of about 20 to 50 NM, considering various practical factors. A special requirement of the study was that one terminal be floating essentially at the water surface, and that the other terminal have a limited elevation ranging between 50 and 100 ft. Our own measurements of attenuation are shown in Figure 3. An unexplained spike in the noise occurs at a distance of about 17 km (9.2 NM).

Since most microwave links are used for terrestrial point-to-point or point-to-multipoint, manufacturers have failed to design an efficient alignment procedure for microwave equipment used at sea. It is almost impossible to line up a microwave antenna on a ship or a buoy because of the three-dimensional motion. For this reason, SeaFi S360 ship stations are different in their design from coastal base station antennas. For example they can compensate for pitch and roll, and they are designed to withstand the pressure of breaking waves.

Another parameter to take into consideration is the Fresnel space factor (Guo & Barton, 2002). The electromagnetic penetration is infinite in a perfectly transparent substance and zero in a reflective material (for example, metals). At the microwave frequency (2.45 GHz, $\lambda = 12.24$ cm), most energy is absorbed by water. This became more obvious as the ship reached the horizon. The line of sight (LoS) horizon for our antennas located at 25 m at sea and 25 m on land was approximately 36 km. As the distance between the two antennas increased, the Fresnel space diameter increased too, causing the signal to hit the sea. The loss of signal occurred at 19.4 NM (approximately 35.9 km). At this distance the Fresnel space radius was over 32.7 m, causing possible signal absorption by sea water too.

MICROWAVE PROPAGATION EXPERIMENT over 35.13 km (6 JUNE 2019)		
Link summary : Rochespoint Lighthouse to OSV Ocean Spey		
Rochespoint		OSV Ocean Spey
51° 47' 34.8" N	Latitude	51° 30' 2.9" N
8° 15' 17.8" W	Longitude	8° 3' 42.0" W
0.00 m	Elevation(ASL)	0.00 m
157.61	Az/mt	337.76
Distance	35.13 km	Distance
25 m	H Antenna	25 m
28 dBm	Tx Power	28 dBm
15 dBi	Antenna Gain	9 dBi
Frequency	2467 MHz	Frequency
Receiver Sensitivity	-94.1 dBm	Receiver Sensitivity
Radio Link Performance		
43.00 dB	EIRP	37.00 dB
19.95 W	EIRP	5.01 W
Free Space Loss	131.2 dB	Free Space Loss
Min. Diffraction Loss	14.90 dB	Min. Diffraction Loss
Vapour Attenuation	0.01 dB	Vapour Attenuation
O2 Attenuation	0.21 dB	O2 Attenuation
-94.32 dBm	RSL	-94.32 dBm
Rain Region / Fade Margin / Availability		
Rain Region	K	Rain Region
-0.2 dB	Fade Margin (FM)	-0.2 dB
-3.1 dB	FM for 99.97%	-3.1 dB
-5.4 dB	FM for 99.99%	-5.4 dB
-8.1 dB	FM for 99.997%	-8.1 dB



Fresnel radius at 17.6 km = 32.7m; ship's antenna elevation = 25 m above mean sea level

MICROWAVE SIGNAL ATTENUATION EXPERIMENT over 38 km (5 MAY 2018 from 20:05 to 21:47)
Average Monthly Temperature: 15.7 – Average Monthly Evaporation: 152.2 mm (Source Met Eireann)

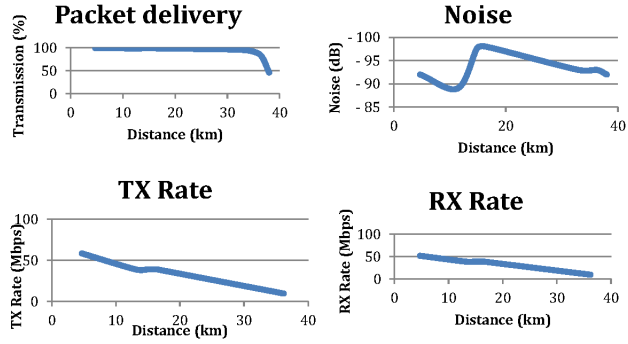


Figure 6 : Fresnel space factor and attenuation curves

5. CONCLUSION

Microwaves have long been used on land and at sea in the form of cellular and satellite communications systems. Coastal communications with the rise of IoT, Machine Learning and Big Data have yet to be invented. It is easier to repair, upgrade and maintain coastal telecommunications systems than orbital satellite equipment at 700 km from earth. Low Orbit Satellites and Nanosatellites are yet to come and will be more expensive than reusing existing structures such as lighthouses. Of all the possible frequencies, 2.4 GHz offers an interesting compromise between atmospheric absorption and gas attenuation. The special design of the SeaFi S360 ship/buoy antenna can cope for pitch and roll with a tilting angle up to 40 degrees. The results of the SeaFi range experiment will change the way scientists retrieve data at sea in the forthcoming years. Incidentally, a claim for the longest wireless broadband transmission at sea has been submitted to the Guinness World Book of Records.

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